Balancing WIP and Throughput with Machine Utilization in a Manufacturing Facility

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***Abstract* – Lean manufacturing is a philosophy with a series of techniques for any manufacturing company to get to the top of production performance and to stay there. But for many still, the teething pains of change and a steep climb are too much to bear and sustain. There are a number of weak points in a company that makes it difficult if not impossible to achieve the promised gains for the efforts they put in. To implement lean requires careful understanding and application of the concepts of throughput, cycle time, work-in-process, and machine utilization. This paper discusses some of the basic lean concepts related to the throughput, cycle time, and WIP that companies should follow when going through the transition to a lean production system.**

***Index Terms* – Throughput, cycle time, WIP, utilization, lean manufacturing, TAKT time, lead time**

I. INTRODUCTION

Companies have adopted lean production principles as a way to reduce costs, reduce lead times, improve customer satisfaction, and increase productivity. The process of becoming lean may mean transforming oneself from one's existing style of operations to an entirely different one. Lean production is a culture and philosophy for an entire enterprise. The process may require significant changes in the functions of the company. Even though there are many examples of companies that have become more competitive and successful by adopting lean production principles and practices, there are many more examples of those who have not been as successful. Many organizations are not clear about what does it take to become lean. To convert from mass production to lean, they relate lean manufacturing to kanban system, or reduction of lot sizes from thousands to hundreds, or making a U-shaped cellular layout. It may not be clearly understood by the companies implementing lean is that kanban or pull system can be used only when it is easy to associate part requirements with the requirements of the finished product. If it is difficult to associate part needs and finished product requirements, then push system is better than kanban system. Many published articles in this area also, do not completely describe the process of going through the gradual and painful progress towards lean manufacturing. A number of companies have difficulty achieving even a fraction of the benefits that studies have shown that a lean environment requires half of the hours of human effort spent on production, one-third of the hours of human effort spent on engineering, half of the factory space to produce the same output with a significant reduction in work-in process (WIP) inventories and defect rate. This paper presents an approach to understand and apply the intricate lean production principles. It will become easy to apply when the principles are properly understood. The paper will not discuss some of the most basic of the lean techniques, namely the 5S, visual factory, total productive maintenance, error-proofing, and multifunctional employees. The paper starts with relationship of lean production with the well-known inventory management principles. The next section shows that the inventory management principles that have been well established in theory and practice, actually develop into the Little's law in lean manufacturing. An example of application of the lean concepts is also shown in a real-life manufacturing industry.

II. SOME LEAN PRODUCTION PRINCIPLES

Generally lean production is considered as a stand-alone concept starting with any application of interest depending on the needs of the industry. However, there exists a natural transition from basic inventory management principles and the development of the concepts of lean production. There is a model called Economic Production Quantity (EPQ) model. Details of this model can be found in any production or operations management text book [1]. Fig. 1 gives a typical quantity versus time graph for this model. As given by (1) the EPQ is calculated by the square root equation given in the figure where, S = Setup cost per setup, D = annual demand in units, *i* = inventory carrying %/year, P = production cost/ piece, *d* = demand rate of the item, and *p* = production rate of the item.

$$EPQ = \sqrt{\frac{2SD}{iP\left(1 - \frac{d}{p}\right)}} \qquad (1)$$

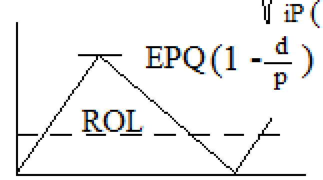

Figure 1. Basic EPQ Model.

A. *TAKT Time*

The maximum inventory that can be reached in this situation is EPQ(1 –*d*/*p*) which can be rewritten as = total production during lead time – demand during lead time. Maximum inventory can be then determined by the relationship,

$$\text{Maximum inventory} = (p\text{-}d) \times LT \qquad (2)$$

where LT = lead time.

It is clear that if *p*-*d* increases, inventory increases. In lean manufacturing, the TAKT time is based on the customer demand rate, thus, TAKT time = 1/*d*. If in a day of 480 min, *d* = 100 parts/day, the TAKT time is 4.80 min/part. A major principle in lean manufacturing is that the production rate

should be made equal to the demand rate to eliminate the inventory build up, that is, $p = d$ should be maintained.

B. Reduction of Lead Time

If $p = d$ is maintained, the maximum inventory to keep in storage is 0 according to (2). This does not include the work-in-process (WIP) inventory. The company is in a state of constant reordering of new material as WIP is finished and shipped. It is well known [1] that Reorder Level (ROL) is given by demand during lead time, that is,

$$ROL = d \times LT \quad (3)$$

Fig. 2 shows that the minimum inventory that a company can have is in the WIP when $p = d$. WIP is also given by throughput (d), and lead time (LT). Lead time includes the raw processing time on machines and the wait time.

Therefore to reduce WIP, the company should concentrate on reducing the lead time. This is an important principle in lean production. The techniques of lean production are geared to highlight the waste in lead times.

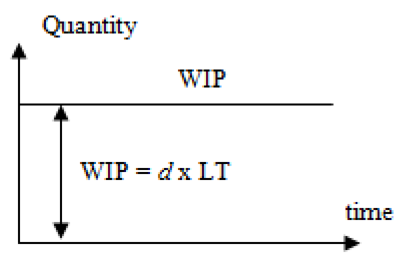

Figure 2. Relationship of WIP and Lead Time.

C. Throughput, Cycle Time, and Utilization

In lean manufacturing, the relationship in (3) is known as the Little's law [2] and is given as:

$$WIP = TH \times CT, \quad (4)$$

where TH = Throughput rate, and CT = Cycle time.

The cycle time CT is the average time from release of a job at the beginning of the routing until it reaches finished inventory at the end of its routing. Minimum CT is simply the summation of the raw processing times at various workstations in a production line.

$CT = \sum T_0$, where T_0 = raw processing time at a station.

For a line with differing processing times, the critical WIP level (W_0) is achieved when the throughput is at its maximum and cycle time T_0 (or CT) is at the minimum. That is,

$$W_0 = TH_b \times T_0, \quad (5)$$

where the throughput rate of a production line is based on the throughput, TH_b, of the bottleneck process in the line.

Machine utilization (U) is traditionally defined as,

$$U = \frac{arrival\_rate}{production\_rate} = \frac{d}{p} \text{ for a steady-state system.}$$

Even though we shall apply this equation for a single product case, this relationship can be easily extended to a multi-product case as well. The above expression can be re-written to determine the utilization of a given machine with multiple identical machines at a workstation as,

$$U = \frac{TH\_of\_the\_line}{(No.\_of\_machines)(TH\_of\_machine)}. \quad (6)$$

Fig. 3 shows four different processes where these concepts can be applied. In Fig. 3(a), there is one machine that has a processing time of 8 hours per job. In 3(b), there are two identical machines each with the same processing time of 8 hours per job. In production lines 3(c) and 3(d), the single machine of 3(a) is replaced by 4 workstations with 2 hours of processing time each. The difference in 3(c) and 3(d) is in the WIP. In 3(c), only one job is allowed as WIP that is when the job is done through the last workstation, another job is brought in to the line. Where as in 3(d), each machine has a job and the total WIP = 4 jobs. When the job at the last machine is done, the first machine takes a new job for the line. Using the lean concepts developed earlier, the results of the performance of the processes in Fig. 3 are given in Table I.

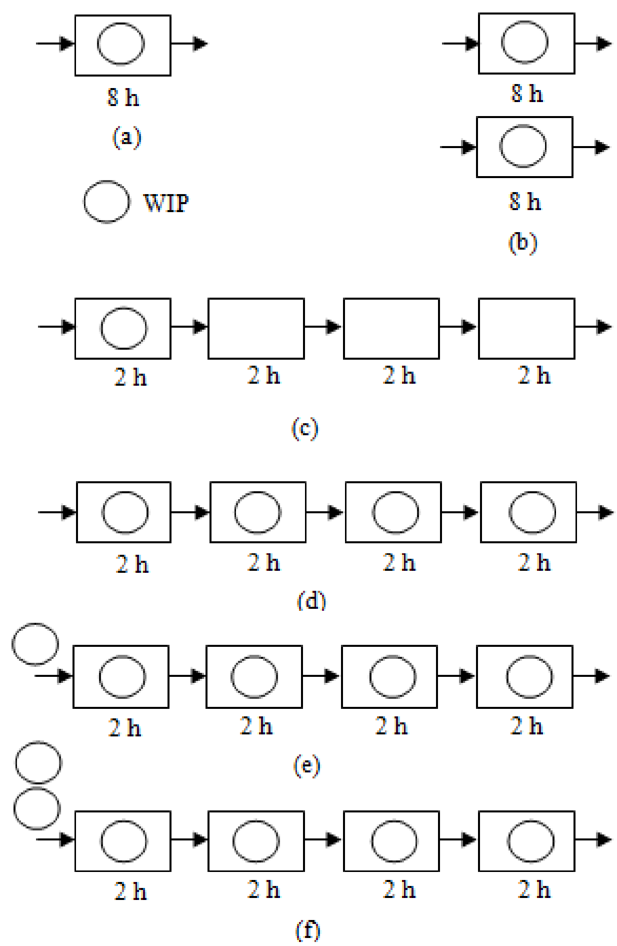

Figure 3. Relationship of CT and TH with WIP in a Balanced Line.

Note that the throughput of line 3d is ½ job per hour which is the TH of each station in a balanced production line with no one process being a bottleneck. A scenario not shown in Fig. 3 is when there are four identical machines like in 3a with processing time of 8 hours each, the CT, TH, and WIP of this process will be the same as the process in 3d. In addition, if in case the process in 3d has unequal processing times, then the TH of the line will be limited by the bottleneck station and would have lower TH and longer CT.

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TABLE I.
PRODUCTION PERFORMANCE OF PROCESSES IN FIG. 3

Process/ Line	CT hours	TH jobs/ hour	WIP jobs	Machines/ station	U %
3a	8	1/8	1	1	100
3b	8	¼	2	2	100
3c	8	1/8	1	1	25
3d	8	½	4	1	100
3e	10	½	5	1	100
3f	12	½	6	1	100

This result concludes that it is better to have independent workstations rather than stations in an assembly line if it is difficult to achieve equal or balanced processing times in the individual stations of the line. However, there may be other factors, such as cost of duplicating the machines that should be considered.

Other principles that can be observed from the results of Table I are:

The CT increases as jobs have to wait thereby increasing the WIP in the system. Machine utilization increases as WIP is increased but up to a maximum WIP given by the critical WIP of W_0. This concept results in temptation to flood the shop floor with enough WIP that the overall machine utilization is increased such that no machine is starved of a job. For balanced lines, the critical WIP is the same as the number of machines.

Consider a scenario where the processing times of workstations in a line are not balanced as shown in Fig. 4. The performance of this line is given in Table II.

Since the processing times are not balanced in the line, the bottleneck process is Machining and the throughput of the line is TH_b = 0.40 jobs per hour.

Some important concepts that can be observed from the results of Table II are:

The bottleneck station is not the one that has the longest processing time (plating) nor is it the one that has the minimum number of machines (lamination). The critical WIP, W_0, is given by TH_b x T_0, that is W_0 = 8 jobs. Note that W_0 is less than the total number of machines in the

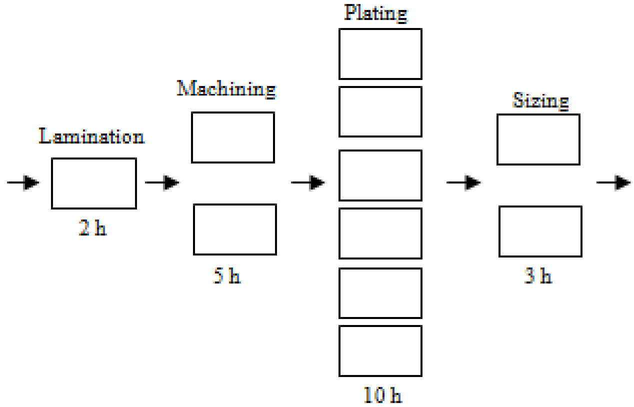

Figure 4. Relationship of CT and TH with WIP in an Unbalanced Line.

TABLE II.
PRODUCTION PERFORMANCE OF PROCESSES IN FIG. 4.

Process	CT hours	TH jobs/ hour	WIP jobs	Machines/ station	U %
Lamination	2	1/2	1	1	80
Machining	5	2/5	2	2	100
Plating	10	0.6	6	6	67
Sizing	3	2/3	2	2	60

line. From this we can conclude that there is excess capacity in the line and not all stations are fully utilized.

III. BEST AND PRACTICAL WORST CASES

The best-case performance can be developed using the results of processes in Figs. 3(c) to 3(f), and with the intermediate scenarios, not shown in the figure, of WIP = 2 and 3 jobs. The general relationship for a best-case performance between CT vs. WIP and TH vs. WIP is shown in Fig. 5 [2].

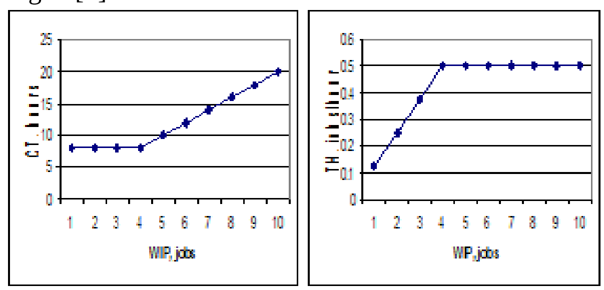

Figure 5. Best-Case Performance of a Line in Fig. 3d.

The best-case is when WIP = 4 jobs as shown in the figure, and this was clear by the results of Fig. 3(d).

In general, equations for the best-case can be easily shown for a given WIP, *w*, as given below:

$$CT_{best} = \begin{cases} T_0 & \text{if } w \le W_0 \\ \dfrac{w}{r_b} & \text{otherwise} \end{cases}$$
$$TH_{best} = \begin{cases} \dfrac{w}{T_0} & \text{if } w \le W_0 \\ r_b & \text{otherwise} \end{cases} \quad (7)$$

Similarly, the practical worst-case performance (PWC) can be developed in which the production line is between the best case and the worst case of maximum CT and minimum TH. The equations for the practical worst-case [2] are given below in (8) and apply to a given WIP, *w*. Their graphs for the line in Fig. 4 are given in Fig. 6.

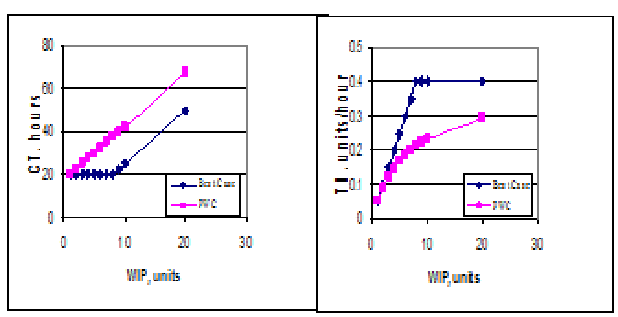

Figure 6. Best and PWC of the Line in Fig. 4.

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$$CT_{PWC} = T_0 + \frac{w-1}{TH_b}$$

$$TH_{PWC} = \frac{w}{W_0 + w - 1} TH_b \quad (8)$$

IV. APPLICATION OF LEAN MANUFACTURING

The lean manufacturing concepts of TH, CT, and WIP have been applied in a simplified but realistic manufacturing plant. A machine shop has one line dedicated to the manufacture of light-duty vent hood shells, but because of strong demand it recently added a second line. The new line makes use of higher capacity automated equipment but consists of the same basic four processes as the old line. In addition, the new line makes use of one machine per workstation, while the old line has multiple machines at the workstations. The processes, along with their machine rates, number of machines per station, and average time for a lone job to go through a station, that is, not including the wait time, are given for each line in Tables III and IV. Simulation run for the two lines over the past 3 months have shown that the old line has averaged 315 parts per day, where one day is an 8-hour shift, and with an average WIP level of 400 parts. The new line has averaged 680 parts per day with an average WIP level of 350 parts. It is important for the management to evaluate the performance of the two lines and to identify potentially attractive improvement paths for each line.

The results of the old and new lines are given in Table V.

TABLE III.
PRODUCTION AT THE OLD LINE.

Process	Parts/hour	Machines/ station	Time, min
Punching	15	4	4.0
Braking	12	4	5.0
Assembly	20	2	3.0
Finishing	50	1	1.2

TABLE IV.
PRODUCTION AT THE NEW LINE.

Process	Parts/hour	Machines/ station	Time, min
Punching	120	1	0.50
Braking	120	1	0.50
Assembly	125	1	0.48
Finishing	125	1	0.48

TABLE V.
PRODUCTION PERFORMANCE OF OLD AND NEW LINES.

Parameter	Old Line	New Line
T_0 min	13.2	1.96
TH_b, parts/hour	40	120
W_0, parts	8.8	3.92
Actual CT, hours	10.2	4.1
Actual TH, parts/hour	39.4	85
WIP, parts	400	350
TH_{PWC}, parts/hour	39.2	119

In the best case, throughput of the new line is 3 times the throughput of the old line. But the actual throughput of the new line is 2.16 times the actual throughput of the old line. The conclusion is that the new line is not running as efficiently as it should. Figs. 7 and 8 show graphically the production performance of the two lines. It is clear that the old line is operating close to the TH_{PWC} whereas the new line is further below from its TH_{PWC}. Therefore, the company should first apply lean techniques of waste elimination, lead time reduction including setup time reduction and achieve balanced production in the new line. However, the current WIP is high for both the lines, and appropriate lean techniques need to be applied to achieve the desired throughput at lower levels of WIP.

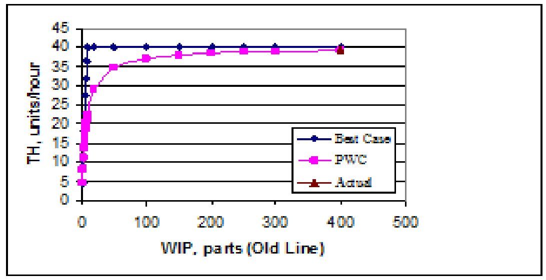

Figure 7. Performance of the Old Line

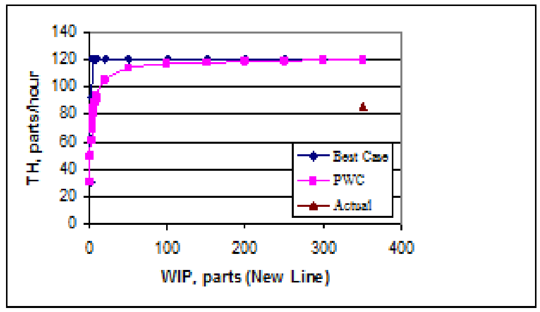

Figure 8. Performance of the New Line.

This practical example shows that the lean manufacturing models can help diagnose a production line and determine whether it is operating efficiently or not. Other tools of lean concept can be used to show ways to improve the current performance levels.

V. CONCLUSIONS

Industry experts estimate that fewer than 5% of US manufacturing firms are truly lean [3]. From Ref. [4], there are two major reasons that industry is lagging in applying lean principles. First one is that lean thinking is counterintuitive to what US management is taught. Using economies of scale, people know that more is better. The idea is that if a company makes large batches of product, the cost per piece is reduced. In lean manufacturing the focus is on value-added activities and the efficiency of the workflow in terms of throughput, cycle time, and WIP that are generated by one-piece flow and shorter distances.

Second reason for the lack of application of lean manufacturing concepts is the basic lack of understanding of lean principles. Ref. 5 showed that there exists a logical flow of application of lean principles. Even though a company may be committed to improve, but valuable resources are wasted in not using the right techniques in the right sequence. Finding focused applications for lean principles, as was shown by the example, a manufacturing company can help get lean program off to a successful start.

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